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Decadal Changes in Global Ocean Annual Primary Production

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Abstract

Blended in situ/satellite data records indicate that global ocean annual primary production has declined nearly 6% from the early 1980's to the present. These comprehensive global data records were derived from revision of the chlorophyll archive from the CZCS (1979-1986) and the modern SeaWiFS (1997-2000), which permitted an unprecedented quantitative comparison of decadal changes. Larger decreases in primary production were observed in the high latitudes. In the North Pacific and Atlantic, these reductions were associated with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans. The results have major implications for the ocean carbon cycle and how it may have changed as a result of climatic influences.

Ocean phytoplankton are responsible for nearly half of the global annual photosynthetic carbon uptake (*1,2*). Despite its importance, reliable global estimates of global annual ocean primary production from satellites have only recently become available (*1*). This is because of the availability of accurate, high quality global ocean chlorophyll observations from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (*1,3,4*), launched in late 1997 and operating until the present. A predecessor mission, the Coastal Zone Color Scanner (CZCS), observed global ocean chlorophyll from 1978-1986, but poor calibration and algorithm deficiencies produced a low quality data set (*5*). Thus an evaluation of decadal changes in global ocean primary production has not previously been possible.

Recently, improved processing methods and calibration have been developed for the CZCS (6) that enhance the CZCS chlorophyll archive to achieve compatibility with SeaWiFS. In addition, application of blending methodologies (*5,6*), where in situ data observations are merged with the satellite data, provide improvement of the residual errors of both CZCS and SeaWiFS. These re-analyzed, blended satellite/in situ chlorophyll data records provide maximum compatibility, which is required for detection of decadal changes. Chlorophyll is the primary input to ocean primary production algorithms (*7-9*). This methodology permits, for the first time, a quantitative analysis of the changes in global ocean primary production from the early-to-mid 1980's to the present (*10*).

Global annual ocean primary production has decreased from the CZCS era (1979-1986) to the present by 5.6% ($P < 0.05$; see Fig. 1). SeaWiFS-era (1997-2000) annual primary production was calculated as 46.2 Pg C m^{-2} y^{-1} (Pg = 10^{15} g), compared to 48.9 Pg C m^{-2} y^{-1} for the CZCS era (1979-1986) (*11*). This apparent long-term decline is roughly the same order of magnitude as El Niño-Southern Oscillation (ENSO) and seasonal scales of variability in global ocean primary production (*1*). The two records each contained a single El Niño and La Niña event.

This decadal decline in global ocean annual primary production from the early 1980" to the present was associated with an increase in global SST of 0.18°C over the same time period (*8*). Warmer ocean temperatures have been shown in models to increase stratification of the surface mixed layer, restricting nutrient entrainment to support ocean

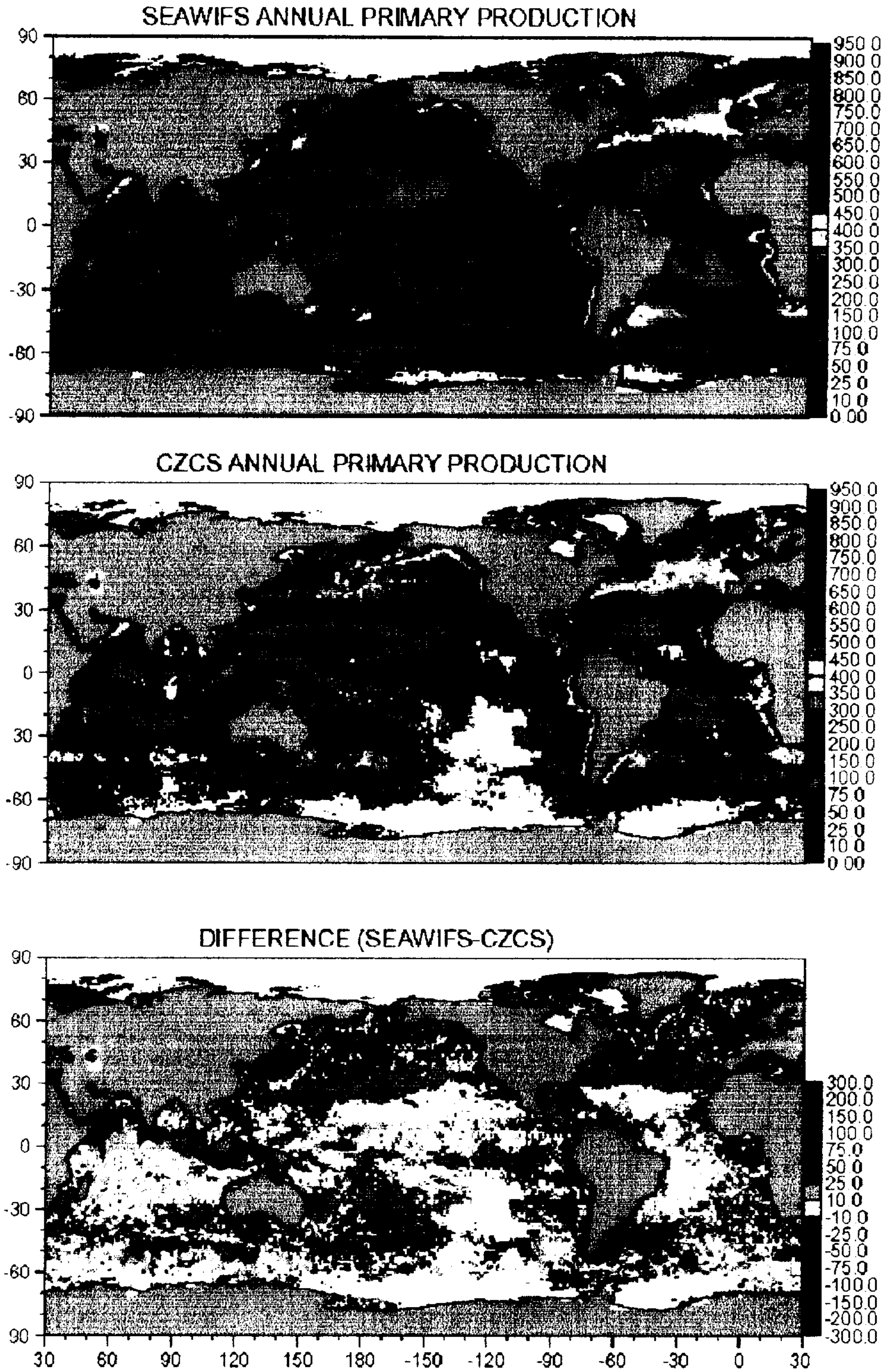

Fig. 1. Primary production distributions for the SeaWiFS era (1997-2000), the CZCS era (1979-mid-1986), and the difference. Units are g C m^{-2} y^{-1}. White indicates missing data.

primary production (*12,13*). These results are consistent with these models and with the increase in SST. Atmospheric iron deposition to the global oceans indicated a decrease of 23% over the two observational time segments (*14,15*). Iron is now established as an important micro-nutrient for ocean phytoplankton and primary production in major parts of the world (*16*), most notably the eastern Pacific Ocean and Pacific sector of the Antarctic. The global reduction in iron deposition observed here is also consistent with the reduction in global primary production.

Climatic influences such as ocean temperatures and iron deposition on ocean primary production are regionally variable in the global oceans. This is true even if the climatic changes are globally uniform, which they are not. We segregated the oceans into 12 major oceanographic basins (Fig. 2), which we use to evaluate the effects of basin-scale annual ocean primary production with some climate change variables, namely SST, iron deposition and surface mean scalar wind stresses (*17*)

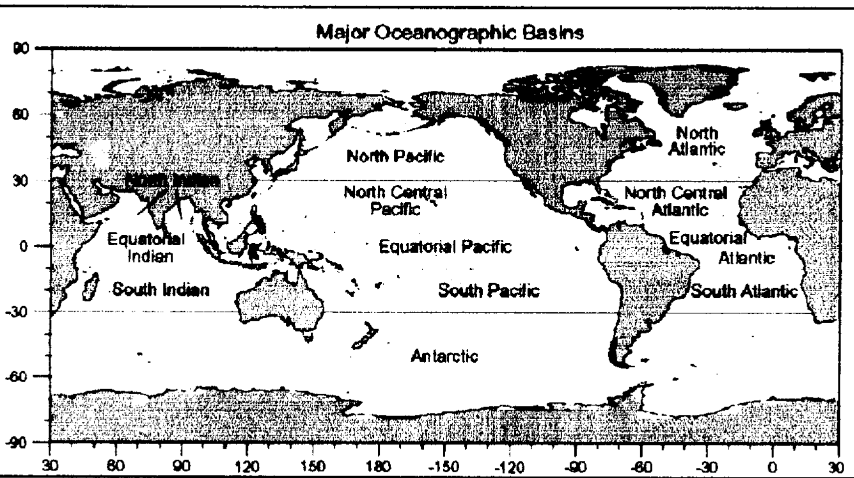

Fig. 2. Boundaries for the 12 major oceanographic basins. Lower limits for the North Atlantic, North Pacific, and Antarctic are set to 30° N and S to capture the difference in the sub-polar frontal zones.

Most of the decrease in global annual pri-mary pro-duction oc-curred in the high latitudes (Fig. 3). The North Atlantic, North Pacific, and Antarctic fell by 8, 13, and 6% respectively over the two decadal time segments. The North Atlantic and North Pacific also experienced major increases in SST: 0.7 and 0.4°C respectively (Fig. 3). These reductions in primary production and accompanying increases in SST are most likely related. Warmer ocean temperatures in these regions increase stratification, as predicted by models, reducing nutrient input to the surface layer. Warmer winter temperatures can inhibit mixed layer deepening, further reducing the supply of nutrients from below during the growing season. Similar long-term reductions in primary production have been observed in the North Pacific by other investigators (*18*), along with decreasing availability of nutrients, which is consistent with mixed layer shoaling associated with increasing SST. The reduced primary production was also accompanied by decreases in iron deposition over the two decadal segments, of 30% and 39% respectively in the North Atlantic and Pacific (Fig. 3). The eastern portion of the North Pacific is limited by iron (*19*), and model studies suggest the North Atlantic exhibits some degree of iron limitation in late summer (*20, 21*).

The Antarctic basin did not exhibit warming over the two decadal time segments, and in fact shows a slight cooling (Fig. 3). Mean scalar wind stresses were much higher in the present (Fig. 3), indicating a 13% increase from the early 1980's. The Southern Ocean operates much differently than its Northern high latitude counterparts. Mixed layers are deep year-round and macro-nutrients (nitrate, phosphate, and silica) are never depleted, even during the maximum growing season. Except where the basin is iron-limited, light-limitation is the rule. The combination of slightly colder temperatures and

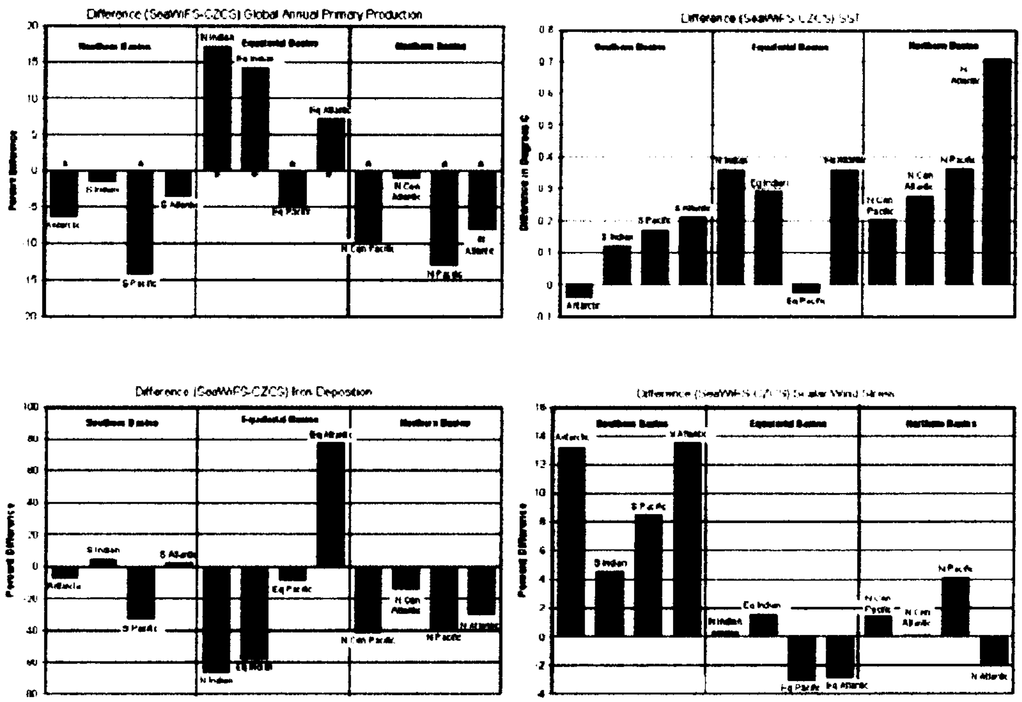

Fig. 3. Differences between SeaWiFS (1997-2000) and CZCS (1979-1986) in the 12 major oceanographic basins. Differences are expressed as SeaWiFS-CZCS. Basin means are area-weighted and only co-located data are used for the comparison. Top left: Annual primary production (%). An asterisk indicates the difference is statistically significant at $P < 0.05$. Top right: SST (degrees C). Bottom left: iron deposition (%). Bottom right: mean scalar wind stress (%).

increased wind mixing will deepen the surface mixed layer and increase the light-limitation. Furthermore, decreases in iron deposition (Fig. 3) exacerbate the situation in the iron-limiting portions of the basin. Even so, a complicated picture of decadal changes in primary production emerged in the Southern Ocean, with major decreases occurring in the Pacific sector east of New Zealand, the sub-polar front in the Indian sector and the eastern portion of the Atlantic sector being compensated by major increases in the Patagonian region and in the Indian sector south of the polar front (Fig. 1).

The low latitude basins, in contrast to the high latitudes, indicated major increases in primary production from the CZCS era to the present (Figs. 1,3). An exception was the equatorial Pacific, which exhibited a small decrease. The increases in the other basins (North Indian, Equatorial Indian, and Equatorial Atlantic) were not directly attributable to any of the ancillary meteorological or oceanic data sets we were able to obtain. The equatorial Atlantic increases were located near the mouth of the Congo River, where record floods have been observed recently (*22*), but no continuous record is available for river discharges during the periods of interest. Increases in the tropical Indian were distributed throughout the Arabian Sea and Bay of Bengal. Substantial decreases in iron deposition were observed (Fig. 3), but these are unlikely to be consequential since iron is not limiting in these regions. Substantial warming has occurred here (Fig. 3), but this would tend to decrease primary production. There are indications that atmospheric depressions and monsoon disturbance days have been decreasing recently (*23*).

Enforcement of consistent processing algorithms between two satellite data records spanning 2 decades, along with blending of both data sets with in situ data to reduce residual errors has enabled us to estimate decadal changes in global annual ocean primary production for the first time. A global decline of about 6% was observed in the analysis of the record, which is of a magnitude comparable to seasonal and ENSO variability. Regional, or basin-scale, decadal changes were even more pronounced. Ocean basins operate with different dynamical and ecological mechanisms, and these differences can have important implications for ecosystem functionality and carbon cycling. Many of the changes are associated with climatic influences, such as ocean temperatures, iron deposition, and wind stresses, that also exhibited decadal-scale changes. The relationship between these events and the change in the basin scale annual primary production is sometimes consistent with model predictions, although a conclusive link is not established here. The decadal decline in primary production in the northern high latitudes and the increase in SST is such an example. It is not clear whether these changes represent a long-term trend or whether they are related to decadal-scale oscillatory events such as the Pacific Decadal Oscillation or the North Atlantic Oscillation.

These results have major implications for the global carbon cycle. The high latitudes typically represent a net sink of atmospheric carbon (*24*). Furthermore, these regions are dominated by diatoms (*25-27*), which typically grow and sink faster than other phytoplankton groups, and thus can represent an important carbon transfer mechanism to the deep oceans. The reduction in primary production occurring here may represent a reduced sink of carbon via the photosynthetic pathway relative to the early 1980's. The low latitudes, conversely, represent a source of carbon to the atmosphere (*28*), although the Equatorial Pacific is the major source and it showed a small reduction. However, for the Equatorial and North Indian basins, and the Equatorial Atlantic, the results here may suggest a reduced low latitude carbon source due to increasing production. Further studies are needed to confirm the influences of these changes in decadal primary production on carbon cycling processes.

References and Notes

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8. Other inputs to the Vertically Generalized Production Model (VGPM, *7*) primary production algorithm are Sea Surface Temperature (SST), daylength, and photosynthetically available radiation (PAR). SST (optimal interpolation fields) and shortwave radiation data records were obtained from the National Center for Environmental Prediction, for the years Jan 1979- Jun 1986 to correspond with the CZCS record, and Sep 1997- Dec 2000 for the SeaWiFS record. The shortwave radiation was converted into PAR (moles quanta m^{-2} s^{-1}, over the spectral range 350-700 nm) using the model of Gregg (*9*). Coastal regions (depth < 200m) were excluded from the computation of primary production.

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10. The SeaWiFS record under investigation here is from Sep 1997 (1st global data acquisition) to Dec 2000 to coincide with public availability of in situ chlorophyll data, which are required for blending to reduce residual errors in the satellite data.

11. These calculations are performed only where co-located valid observations of chlorophyll from CZCS and SeaWiFS exist, and are consequently lower than an actual global total.

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